NUTRIENT LOSSES IN LEACHING AND EROSION BY INTENSIVE FOREST HARVESTING

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Abstract.--Deep leaching and erosion are both pathways of nutrient loss from sites following intensive harvesting. Temporary increases in leaching losses may degrade surface-water quality, but generally will not be great enough to measurably decrease site quality under well-managed harvest and post-harvest conditions. Amounts of nutrients lost in erosion can be very great, especially from associated road construction. Mechanisms of leaching are understood, and leaching rates are relatively easily measured and may even be predictable in some cases. In contrast, erosional losses are difficult to measure, and often difficult to predict or control. Good engineering in both road placement and harvesting method can greatly minimize losses. Future work should concentrate on combined watershed/small-plot studies over a wide range of site conditions, with realistic treatments. More attention should be given to soil properties, microbiological processes, and atmospheric inputs, and their interactions with intensive harvesting, especially "whole tree" techniques. Emphasis in assessing the importance of leaching and erosion should be directed at determining loss of productivity, and not simply the amount of nutrient movement.

Additional key words: Ion transport, anion mobility, soil solution, forest soils, clearcutting, nutrient cycling, watersheds, site quality, productivity.

INTRODUCTION

Forest harvesting obviously removes nutrients from the ecosystem. Conventional harvesting removes about 5-30% of the total nutrients taken up in the aboveground stand (Stone 1975), but the average for most forests rarely exceeds 10%. Breaking the cycling process can also trigger losses through three primary pathways: by volatilization to the atmosphere (e.g., gaseous forms of nitrogen), by movement of ions in the soil solution beyond the rooting zone and hence to drainage waters (e.g., Ca, Mg, K, NO_3), and by soil erosion (e.g., phosphorus adsorbed to soil particles). We will discuss these latter two pathways of loss. The pathways are similar only in that the nutrients are carried by water. They differ in that leaching losses, and the factors that affect them, are primarily chemical; whereas erosion losses, and their controlling factors, are primarily physical. We outline the

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principles that exist to help explain these processes, and discuss the application of these principles to the topic. In doing so we will use examples and quote data, but our primary aim is to establish some basic principles, and to focus on the state-of-the-art, so that future studies and applications will be both logical and efficient in design and purpose. Attempting to discuss dissimilar pathways in a single integrated review is difficult. We shall therefore discuss each pathway separately, and then draw them together in our concluding remarks.

LEACHING LOSSES

Principles of Nutrient Cycling

The frequently used term "accelerated leaching losses due to intensive forest harvesting practices" implies that there are leaching losses from undisturbed forest ecosystems, and that these losses are intensified during or after forest cutting. It also implies that nutrients either act as a whole, or at least, act similarly. In many cases such implications are correct, but in other cases additional qualifications are required. As an introduction, the broad principles that need clarification are those relating to nutrient cycling processes in terrestrial ecosystems.

Nutrient cycling in forests largely involves the "biological cycle" i.e., movement of nutrients within the soil-plant-water system, in contrast to larger cycles such as those involving geologic uplift, volcanic activity, or gross erosional events. Inputs to such biological cycles come from the atmosphere and from weathering of soil parent material. A young forest rapidly "fixes" nutrients in the biomass from these sources: e.g., carbon and nitrogen are fixed from gaseous atmospheric sources, whereas most cations, sulfur, and phosphorus are absorbed from the soil. Thus, nutrient uptake in a young forest far exceeds return. Losses back to the atmosphere or to the aquatic environment (as erosion or in drainage waters) are small. As a forest ages, uptake decreases, and at "maturity" a state of "semi-stable equilibrium" is reached where internal cycling is maximized and where outputs equal inputs.

Stone (1975) enumerated three different types of interest in nutrient transformations and losses associated with timber harvesting: altered concentration of chemical elements or ion species in runoff, changes of mass balance, and vegetation response to nutrient transformations and losses. Each of these types of interest involve different types of measurements over different time-scales. Sources of variation in studies are due to differences in tree species, time of cutting, local precipitation and temperature patterns, topography, soil and geologic characteristics, the method of cutting and timber removal, and post-harvest regeneration or planting techniques. Misrepresentation of experimental results in some cases has largely been due to our limited understanding of interactions of these factors.

The Soil Factor

One of the most important factors is the soil, as it is both the source and sink of many nutrients, and is a major component in the biological cycle that is perturbed by timber harvesting. It is also the ecosystem component linking the vegetation and aquatic components, and is thus in a strategic position to "buffer" effects of terrestrial management practices on water quality and quantity.

Timber harvesting involves disturbance (and often removal) of the litter layer and of the upper mineral soil horizons. Effects are not limited to just these surface horizons where physical disturbances are obvious; e.g., lower soil horizons usually retain greater moisture following forest cutting due to the decrease in evapotranspiration. Such increased soil moisture often results in anaerobic conditions, and solubilities of certain nutrients can be changed with this shift from oxidizing to reducing conditions (McColl 1978).

Historically, soil scientists have focused most attention on movement and retention of cations in soil (Bolt 1967). For example, cation exchange phenomena and methods for determining cation exchange capacity (C.E.C.) are widely-known and well-understood, whereas less is known about anion behavior. Most anions are not as readily adsorbed by soil as are cations, and are thus assumed to be "mobile" in the soil solution. Recently, more attention has turned to anion behavior because of the practical implications; the amount of mobile anions in solution largely determines the amount of cations in solution, and thus is instrumental in affecting cation leaching losses.

Mechanism of Ion Leaching and Retention

According to the concept outlined by Nye and Greenland (1960), later by McColl and Cole (1968), and elaborated by others (e.g., McColl 1972, Cole et al. 1975, Johnson and Cole 1977), cation leaching is largely controlled by the presence of mobile anions in solution, because the solid phase of the soil has a large component of immobile negative charges commonly called the cation exchange complex (C.E.C.). Hydrogen ions, accompanying the mobile anions, exchange with cations from the C.E.C. These displaced cations subsequently move in the soil solution with the unadsorbed mobile anions. If the cation-anion balance of the soil solution is altered temporarily by the addition or subtraction of one ionic species, the electro-chemical balance is restored by an equivalent change in concentration of oppositely charged ions.

Such changes in ion balance can be caused by soil disturbances during forest cutting; leaching of cations in undisturbed forest soils is small because of the lack of mobile anions in solution (McColl and Cole 1968). To sum up so far, the solubility and retention of nutrient cations in soil are determined not only by the bonding energy of cations, but also by the kind of the associated anion. This viewpoint is now receiving more deserved

attention, particularly as additional anion inputs to the soil from polluted atmospheres (e.g., "acid rain" inputs) and from soil additives (e.g., sewage effluent waters) also change the soil leaching process as it occurs in unperturbed ecosystems (Johnson et al. 1979, McColl 1978, McColl and Bush 1978, Cronan et al. 1978).

The leaching process itself has also been studied and formalized in more detail in recent years (Wiklander 1975/76). The effectiveness of the predominant anions in the process of cation leaching is generally: $PO_3^{3-} < HPO_4^{2-} < H_2PO_4^- < SO_4^{2-} < NO_3^- \sim Cl^- \sim HCO_3^-$. This series also describes the relative "mobility" of these anions in the soil solution.

There are many sources of mobile ions. Two of the most mobile anions are produced in important reactions that take place during decomposition of organic matter in the soil; respiration results in the bicarbonate ion, and nitrification results in nitrate. In undisturbed temperate forests, bicarbonate usually is the dominant anion in the soil solution; it is formed when CO_2 from respiration dissolves in water in soil with pH 4.5-8.3 Sometimes carbonate dominates when the pH exceeds 8.3, although this pH is unusual in forest soils unless alkaline fertilizer-salts have been added or where leaching of basic ash material occurs following burning. Nitrate concentrations are low in undisturbed forest soils relative to those in many agricultural soils, as nitrification is negligible below a pH of 5 or 6 (Alexander 1961). However, under certain conditions, clearcutting may trigger increase in nitrification rates and effectively increase cation leaching (Likens et al. 1970), even at apparently lower soil pH levels (although microsites where nitrification is taking place may have pH above 6). Chloride, and to a lesser extent, sulfate are also mobile in the soil solution, but their concentrations are normally very low in undisturbed forest soils unless there are local atmospheric sources. For example, chloride inputs may come from the ocean. In coastal areas, removal of the vegetative cover and/or litter layer during a timber harvest can cause increases in chloride ion relative to other anions in the soil solution; where air pollution by sulfur dioxide occurs, the soil solution can have relatively high sulfate levels (McColl 1978).

If such anion inputs exist, the loss of nutrient cations from soil will be further accelerated if there is increased downward flow of water due to the removal of transpiring vegetation. It is obvious, then, that the process of ion transport in a forest soil (and, the subsequent removal of these nutrient ions from the soil system), could be greatly magnified when a number of the above conditions coincide. The problem is to know the prevailing conditions in the undisturbed condition, and then to predict changes due to various ecosystem perturbations.

The relatively immobile anions do not pose a problem. In fact, they may even increase the retention of cations in the soil, rather than increase leaching. Phosphate is always adsorbed more strongly than sulfate, but both phosphate and sulfate, when "specifically" adsorbed (Hingston et al. 1967), actually increase

the net negative charge on soil colloids, thus increasing the C.E.C. This adsorption restricts the mobilities of these anions, especially in sesquioxide-rich soils (Mekaru and Uehara 1972) and thus increases the retention of nutrient cations. Phosphate is also readily "fixed" in soil as well as adsorbed; phosphate precipitates of Al or Fe occur in acid soils, and those of Ca occur in alkaline soils. Thus, nearly all soils strongly adsorb or fix phosphate, rendering it immobile and thus unable to facilitate cation leaching.

Organic acids and colloids may also influence the transport of cations (Wiklander 1958). Production of organic acids is largely controlled by the same environmental factors as those controlling the bicarbonate concentration (McColl 1972), namely, temperature and moisture regimes and the nature and amount of organic matter. Johnson (1975) substantiated this control in his study of soil leaching processes in forests over a wide climatic range. He found that carbonic acid leaching decreased and organic acids became proportionally more important with decreasing annual temperature, i.e., in sub-alpine and cold environments. Similar results have been found in cold-region Russian soils (e.g., Ponomareva et al. 1968).

Effects of Forest Harvesting

With these principles and processes now fairly well-established, it is pertinent to review the magnitude of leaching losses and to address the problem of predicting the effects of intensive forest harvesting. Excellent earlier reviews include those by Sopper (1975), Stone (1975), and Stone et al. (1978) and not a great deal can be added to these reviews, other than to quote results of additional monitoring studies.

Clearcutting opens up an area, permitting additional light, heat, and moisture to reach the forest floor and mineral soil, thus accelerating decomposition in most cases. The amount of soluble inorganic ions and organic compounds moving from the decomposing slash and disturbed forest floor is largely controlled by these environmental factors, and by the amount and chemical composition of the organic matter. Williams and Gray (1970) present a good discussion of factors affecting litter decomposition. The amount of nutrients actually lost from the forest ecosystem to drainage waters depends on both the above environmental factors and also on the post-harvest conditions.

Fast-growing tree species, from natural regeneration or plantings, quickly recycle nutrients within the ecosystem, thus minimizing leaching losses. A well-designed and implemented harvest, followed by equally good regeneration, will not result in significant nutrient losses from the soil and will usually cause only temporary increases in nutrient concentrations in surface drainage water. Stone (1975) estimated that nutrients removed by harvesting stemwood and bark are generally in the range of 10-30 kg/ha for P, 50-300 kg/ha for N, and 100-1,000 kg/ha for Ca, and that these amounts can usually be replaced by uptake from the soil by the subsequent forest stand. Stone does add, however, that

these amounts could be multiplied two to four times as conventional above-ground tree harvesting techniques are replaced by whole-tree harvesting techniques in which limbs and even roots are removed. Such intensive practices will also cause greater site disturbance and could lead to greater nutrient loss through soil leaching and soil erosion, particularly as intensive management usually implies shorter rotations and thus more frequent site disturbance (Armson 1977). Implications of whole-tree harvest techniques and shorter rotations on nutrient removals are also discussed by Boyle and Ek (1972), Weetman and Webber (1972), and are the topic of other speakers in this symposium.

Experimental Techniques

Most experimental studies of leaching losses following forest harvesting have used either (1) input-output monitoring with small watersheds, or (2) lysimetry studies in small plots. Both techniques have yielded much needed data. While the results obtaind from each of these techniques are similar, we must not always equate them.

The watershed approach generally yields good results of overall inputs and outputs (e.g., atmospheric precipitation and streamflow), but does not allow explanation of processes within the watershed unless interpolations are made or additional studies are carried out. The small-plot approach, on the other hand, allows dissection of a forest ecosystem, and is based on more-detailed studies, usually designed to elucidate internal cycling processes (e.g., Cole et al. 1975). However, extrapolation is required to extend small-plot results to a realistic ecosystem level. Such extrapolations may grossly magnify errors; for example, volumes of soil solution flow (and hence nutrient amounts) calculated from small-plot lysimetric data usually lead to large errors when extrapolated to estimate stream flow (and hence nutrient losses) in an entire watershed. Clearly, a combination of watershed and small-plot studies is most desirable.

Watershed Studies and Nitrogen Losses

The small book by Likens et al.(1977) has a good summary table, listing nutrient inputs and outputs for various terrestrial ecosystems (primarily forests) of the world. The authors point out that these input-output budgets have many patterns in common with those at Hubbard Brook, New Hampshire. In summary, P and N inputs in bulk precipitation are generally greater than losses in drainage waters on an annual basis, whereas Ca, Mg, Na, and K inputs are small compared to out~~in~~puts. Input-output budgets for S are variable with geologic substrate and intensity of air-pollution. In the undisturbed watershed at Hubbard Brook, total losses of dissolved substances and particulate matter are 198 kg/ha.yr in stream water, about 1.5 times greater than the total inputs in bulk precipitation of 134 kg/ha.yr. The difference is made up by rock weathering within the watershed (Likens et al. 1977).

Controversy over Hubbard Brook arose from the results from the treated watershed (Likens et al. 1970), which indicated exception-

ally large losses of NO_3-N and associated cations, with streamflow nitrate concentrations as high as 82 mg/ℓ, and 53 mg/ℓ even two years after cutting. In many other forest ecosystems, cutting caused only modest increases in NO_3-N in streams with values averaging about 1 mg/ℓ or less (e.g., Aubertin and Patric 1974, Fredriksen et al. 1975, Gessel and Cole 1965, Kimmins and Feller 1976). Stone et al. (1978) have already discussed the results of the Hubbard Brook study, which can largely be explained by the fact that the clearcut watershed also received a herbicide treatment, thus preventing any regeneration that would have absorbed nitrate released from the large amount of decomposing vegetation that was left on the watershed.

Deficiencies in Past Studies and Points for Future Studies

The Hubbard Brook workers (Likens et al. 1977) highlight a major deficiency common to most watershed nutrient-cycling studies, namely that microbiological investigations do not parallel those of inorganic nutrient cycling processes. One of their main conclusions was: "Many of the important biogeochemical relationships within the forested ecosystem are regulated by microorganisms. Unfortunately, we know relatively little about the transformations mediated by microbes, such as nitrogen fixation, nitrification, and denitrification, or sulfur oxidation and reduction at Hubbard Brook. These aspects of nutrient cycling as they relate to nutrient flux must be more carefully evaluated in future studies".

Nitrogen cycling is complex, and at first sight, study of certain aspects of it presents some unusual results. For example, litter during its first year of decomposition may actually have an absolute increase in its N content due to increases in N-fixing bacteria (Grigal and McColl 1977, Tchagina et al. 1968, Gosz et al. 1973). The higher N content may result in temporary immobilization of P and K in microbial tissue. Eventually, upon death of these organisms, P, K, and the additionally-fixed N are available for leaching. Estimating such absolute increases due to N-fixation is beyond reach at present; baseline data are lacking because techniques of measuring N-fixation, and denitrification also, are currently inadequate under field conditions, at least at the ecosystem level.

Another deficiency in many studies of nutrient losses due to harvesting is the scarcity of adequate descriptions of soils. It is clear that most nutrient cycles intimately involve the soil, yet it is practically impossible to glean sufficient information about the soils from the various reported studies, for the purpose of drawing up even the most elementary comparison table. Classification of the soil according to Soil Taxonomy (Soil Survey Staff 1975) provides considerable information about soil morphology. A table of simple soil physical and chemical properties including particle size distribtuion, bulk density, water retention, C.E.C., and pH, would also be useful. If we are to understand such processes as nitrification, nitrogen fixation, cation leaching, and decomposition of organic matter, we must gain more knowledge of soil

properties and how they might be affected by site manipulations. Soil-plant interactions, especially in the rhizosphere, must also be given more detailed attention.

Comparison of effects of intensive harvesting in different locations is possible only when the factors controlling nutrient releases and movements are understood. The importance of the soil factor, for example, was shown in a study by McColl (1978), in which decreases in concentrations of K, Ca, Mg, nitrate, and bicarbonate in the soil solution occurred following clearcutting. This is in contrast to results of other studies quoted earlier, where concentration increases were generally noted. But the results are explainable to a large degree by the soil and climatic conditions; the soil was a Typic Arigxeroll (a clay-loam with a high C.E.C.), rainfall was low (56.8 cm/yr) and limited to only a few months (usually December to March), and much of the slash and litter was removed during the harvest.

Future studies of nutrient leaching losses should ideally use a combination of the watershed and small-plot techniques, in which realistic management practices are simulated over a wide range of site conditions. Greater study should be made of soil characteristics, microbiological processes and atmospheric inputs, and of their interactions with intensive forest harvesting.

EROSION LOSSES

Evaluating Effects of Erosion

In this discussion, we are concerned with accelerated erosion due to intensive forest harvesting, and not with geologic erosion associated with weathering under relatively undisturbed conditions. It is fairly clear that accelerated erosion is undesirable. To determine precisely why this is so, we may have to enter into value judgements. Erosion can adversely affect water quality, to the detriment of the aquatic ecosystem; the consequences of erosion are aesthetically unpleasing; erosion results in reduction in productivity of eroded areas; and in summary, erosion is a diminution of the soil resource. Our discussion will concentrate on the reduction in productivity associated with erosion. We shall primarily point to gaps in information, rather than to areas where we have some basis on which to make management decisions.

We do not plan to make a detailed review of causes and mechanisms of erosion from forested systems, as many reviews have already been published, including those by Dyrness (1966), Megahan (1972), Patric (1976), Rice, Rothacher, and Megahan (1972), Stone (1973), and Swanston and Swanson (1976). For completeness we will briefly describe the major kinds of surface erosion and mass flow (drawing heavily on the excellent review of Swanston and Swanson (1976)) before we discuss the impacts of those processes.

Types of Erosion

Surface erosion is the movement of individual soil particles

along the surface of the ground. Soil particles are detached from the soil surface and either moved downslope by raindrop splash (sheet erosion) or carried in suspension by flowing water (rilling and gullying) (Dyrness 1966). The extent of surface erosion depends on the ease with which soil particles can be detached and transported; the forces available for transport, including raindrops, wind, surface flow and gravity; and the materials such as natural litter, logging debris, mulches, and surface rock, that protect the soil (Megahan 1972).

Mass flow processes are the dominant mechanisms of sediment transport from hillslopes to stream channels in the Pacific Northwest (Swanston and Swanson 1976) and in other mountainous areas. The principal mass erosion processes are slow downslope movement with subtle deformation of the soil mantle (creep) and discrete failures, including slow-moving deep-seated slump-earthflows; rapid shallow soil and organic debris movement from hillslopes (debris avalanches); and rapid debris movement along downstream channels (debris torrents). Because these processes are important in the transfer of soil materials, we will describe them in somewhat greater detail.

Creep is the slow downslope movement by quasi-viscous flow of the soil mantle in response to gravitational stress. Shear stresses are sufficient to produce deformation but too small to cause failure. Creep, the most persistent of all mass erosion processes, results in a continuing supply of soil material to streams at rates of a few millimeters to a few centimeters per year. A large quantity of soil is delivered and the supply is continuous.

Slump-earthflow, similar to creep, occurs where shear stresses are great enough to cause discrete failure. Slumping is rotational movement, while in slow earthflow the moving material is broken up and transported downslope. Size of area and thickness of material involved vary widely from hectares to square kilometers, and meters to tens of meters. Because of their nature as slow-moving, poorly-drained features, movement is mainly determined by bedrock geology.

Debris avalanches are rapid, shallow-soil mass movements from hillslope areas, including debris slides, avalanches, and flows. They are usually triggered by infrequent, intense storms, and leave scars in the form of spoon-shaped depressions from which less than 10 to more than 10,000 m^3 of soil and organic debris have moved downslope. They occur on steep slopes where shallow non-cohesive soils overlie bedrock or glacial till subsurfaces where water collects.

Debris torrents involve the rapid movement of water-charged soil, rock and organic material down steep intermittent first- and second-order stream channels. They are triggered during extreme discharge events by slides from adjacent hillslopes, which enter a channel and move directly downstream, or by debris avalanches along the track of the torrent. When a torrent loses momentum, there is deposition of a tangled mass of large organic debris in a

matrix of sediment and fine organic material covering areas up to several hectares. Channel characteristics, such as amount of debris and peak discharge, primarily control their occurrence.

Closely interacting mass flow processes are major links in movement of soil to streams. Areas of creep and slump-earthflow activity may overlap, and these two processes contribute to instability leading to debris avalanching. Debris avalanches, in turn, initiate debris torrents.

Rates of Erosion and Nutrient Losses by Erosion

Natural surface erosion. Geologic rates of surface erosion are relatively low. Data from eastern forests (Patric 1976) and from Idaho (Megahan 1974) and Colorado (Leaf 1974) indicate rates of soil loss of about 100 kg/ha. yr from undisturbed forests. If the bulk density of the surface soil was 1.0 g/cm^3, 100 kg/ha. yr loss leads to a loss of 1 cm every 1,000 years from the soil surface.

The loss of nutrients from the site associated with these rates depends on the fertility of the soil. At the rate of loss of 100 kg/ha. yr, a system will lose 100 g of N for every 0.1% N in the surface soil, and 20 g of Ca, 12 g of Mg, and 39 g of K per meq/100 g of each of these elements. It is not unreasonable, therefore, to assume a loss of about 100 g/ha. yr of N and Ca and about 25 g/ha. yr of Mg and K, based on analysis of surface horizons of forest soils (Geist and Strickler 1978, Paeth et al. 1971). These losses are at least an order of magnitude less than deep leaching losses from a number of undisturbed forest ecosystems (Stone 1973).

Accelerated surface erosion. Accelerated surface erosion is primarily related to road construction (Patric 1976, Megahan 1972, Rice et al. 1972). Accelerated rates related both to roads and to the harvest decline exponentially with time (Megahan 1974); the decline in rate is therefore much more rapid in the first 2 to 5 years after disturbance. As a result, studies which determine the maximum rate immediately following road construction or harvest will over-estimate loss because that rate is not maintained. Counter to this, many studies which assess loss over a 5 to 10 year period do not usually report the maximum rate.

A broad estimate for soil loss by surface erosion over a 5 to 10 year period following road building and harvesting is between 1000 and 5000 kg/ha. yr. This is slightly more than an order of magnitude greater loss than rates of geologic erosion. Nutrient loss associated with such erosion rates may equal those occurring by deep leaching under natural conditions.

Natural Mass Erosion

Evaluation of natural rates of mass erosion is difficult because in some cases rates are very slow, and therefore difficult to measure; in other cases, events are associated with severe storms, and may therefore occur infrequently but move large quantities of

material. Each kind of mass erosion has different effects, depending on the size of the soil body affected and the amount of movement. Soil creep has been estimated to supply about 15% of the sediment to streams in north coast watersheds of California (Anderson 1971). In areas characterized by deeply weathered, clay-rich mantle materials, creep movement may range as high as 15 mm/yr (Swanston and Swanson 1976).

Movement rates of earthflows vary from imperceptibly slow to more than 1 m/day in extreme cases. However, these average rates are somewhat misleading because of the great variability of movement rate over both time and space. Movement rates of debris avalanches have seldom been measured because of the extreme storm conditions under which they occur, but their rates of movement probably range as high as 20 m/s. Annual rates of debris-avalanche erosion from forested areas in Oregon, Washington, and British Columbia range from 150 to 1,000 kg/ha. yr (Swanston and Swanson 1976).

Velocities of debris torrents, estimated to be up to several tens of meters per second, are known only from verbal and a few written accounts. Debris avalanches have played a dominant role in triggering torrents (Swanston and Swanson 1976). Following a 50-year storm on the H. J. Andrews Experimental Forest in Oregon, mass movements mobilized about 10,500 kg/ha in the undisturbed portion of the watershed (Dyrness 1967). Mass movements under undisturbed conditions are therefore capable of mobilizing large amounts of material. However, if we allocate this movement over the entire 50-year period, then rates of loss are about 200 kg/ha. yr, similar to rates of surface erosion.

Accelerated Mass Erosion

Roads are also implicated in mass erosion (Rice et al. 1972, Megahan 1972). Dyrness (1967) found that 72% of the mass erosion following the severe storm in Oregon was associated with roads, which occupied only 2% of the area. Roads interrupt the strength-stress relationships existing under natural conditions by cut and fill activities, poor construction of fills, and alteration of surface and subsurface water movement (Swanston and Swanson 1976). Logging may also contribute to mass erosion both through increased water in the soil mass due to reduction in transpiration and through reduction of the living root mass which tends to hold unstable soils in place (Rice et al. 1972).

Creep rates are probably accelerated by clearcutting and road construction, and slump-earthflows definitely are (Swanston and Swanson 1976). Once areas have been destabilized, they may continue to move for several years. Clearcutting alone accelerates debris avalanches by 2 to 4 times, and roads by 25 to 340 times (Swanston and Swanson 1976). These increases in turn lead to increases in debris torrents.

Following the 50-year storm at H. J. Andrews Experimental

Forest in Oregon, 35% of the material moved by mass erosion was associated with earthflows and 64% was associated with channel scour (Dyrness 1967). Earthflow movements amounted to about 8,000 kg/ha on an entire watershed basis, and channel scour to about 14,000 kg/ha. About 59% of the material moved occurred in the 15% of the watershed that had been disturbed by road construction and logging.

Site Quality Reduction Due to Erosion

Reduction in productivity associated with erosion can be caused by changes in either soil chemical or physical properties that make the soils less amenable to tree growth. The simplest cases to treat are those associated with chemical changes, and especially with nutrient losses. The surface of most soils contains a greater proportion of nutrients per unit weight than does the subsurface. Removal of the surface soil removes nutrients from the site, and conceivably could have as great or more impact on productivity as removal of the product. In addition to removal of nutrients from the site, erosion exposes the lower-nutrient subsurface, which is likely a poorer medium for plant growth.

Soil physical changes include removal of the friable surface and exposure of the often more massive, less permeable subsurface; in some cases this may even lead to removal to bedrock. The result is reduced tree growth per unit area, and in some cases an accompanying reduction in the area.

The extent of erosion following harvesting is difficult to determine. Small plots or catchments may not provide realistic data for the evaluation of erosion over an entire watershed. Erosion may be under-estimated because of the belt of no erosion near the upper boundaries, or may be overestimated because no opportunity for downslope deposition exists (Rice et al. 1972). Many features of small plots are not representative of entire watersheds, such as a uniformity of treatment and absence of large-scale processes (Rice et al. 1972). Even if measured precisely, does displacement of surface material a few centimeters or even meters on a site constitute sufficient cause for concern regarding loss of productivity?

Evaluation of loss of productivity associated with mass erosion events is more difficult. In some places, only downslope displacement occurs, but the site may still remain productive for forest trees. Material that is lost from the system may be derived from the subsurface and not the surface soil, and therefore is not as high in nutrients as is surface soil.

The response of streams to harvesting activities, as measured by sediment transport, is also nebulous. Harvesting, by decreasing transpiration, increases streamflow. The result of an increase in streamflow is a greater capacity of the stream to carry sediment, which in many cases may be scoured directly from the stream banks or bed (Anderson 1971). If we measure soil loss by sediment production, that number may be relevant to a stream biologist as a

parameter of water quality. But that number also does not deal with the real issue from our perspective at this symposium, and that is, what is the loss of productivity?

Deficiencies of Past Studies, and Points for Future Studies

How can we evaluate the loss of productivity associated with harvesting? Despite measurement problems, the literature contains extensive data on the amount of soil loss, measured in mass per unit area per time, under different conditions. What exactly do those numbers mean? In most cases of surface erosion associated with harvesting, the accelerated erosion declines exponentially with time so that within three to five years it is back to a low rate. Because of the destabilizing effect of vegetation removal, mass erosion may be accelerated following disturbance for two to three times longer than that.

It may be difficult to document reduction in growth rate of trees growing in eroded areas compared to those in uneroded areas, because of the many other environmental and genetic factors that affect such growth. On complex slopes, where deposition of eroded material at downslope positions is likely, there may even be enhanced growth. The problem of balancing potential growth reduction and enhancement sounds prodigious.

Why hasn't productivity decline been more widely measured? There are a large number of conceivable, and some inconceivable, problems in its measurement. We probably need longer time periods of measurement than do the agronomists when they assess the loss of productivity associated with erosion in agricultural soils. Erosion may cause establishment problems, but once established, trees grow well. How do we assess that decline in productivity? It should most meaningfully be assessed over the life of the stand.

Road construction has been indicted, and in fact acknowledged, to cause the most significant erosion, no matter what the harvesting system. Pages have been written concerning careful placement and construction of roads, using all available knowledge about potential erosion associated with various geologic deposits. There is definitely a loss of productivity associated with the road itself. Though often not considered erosion, the removal of surface soil and/or the addition of low-nutrient fill, with subsequent compaction, reduced the area on which the next tree crop grows. Estimates of area directly occupied by roads varies with the logging system, but a loss of 5% or more of the site is possible.

The economics of loss in productivity from erosion must be considered. Although roads are major causes of erosion, they are necessary for good management, including not only harvesting but site preparation, planting, cultural treatments, and fire control. Are we willing to sacrifice some measurable productivity (if it were or could be measured) as the price of the road network? The greatest amount of accelerated erosion associated with road construction may only occur once at a site, when the permanent road

system is established. Certainly a road system should be judiciously established, but in some terrains, almost any road will cause problems.

CONCLUSIONS

1. Effects of intensive harvesting on nutrient losses by leaching vary with tree species, times of cutting, local precipitation and temperature patterns, topography, soil characteristics, methods of cutting, techniques of timber removal and post-harvest practices. Unless erosion or major disturbance of the litter layer occurs, nutrient losses will be minimal, due to retention in the litter and soil and to uptake by rapidly growing regeneration. However, if slash is left to decompose, if regeneration is inhibited, or if the litter and soil are disturbed, leaching will be accelerated and nutrient losses will occur if there is sufficient precipitation. Such losses may degrade surface water quality, but the extent of effects on forest site-quality is probably small or negligible in most cases.

2. Theories of leaching processes are generally explained, and the techniques used in studies of nutrient leaching losses are generally adequate. We encourage studies in which a combination of watershed and small-plot techniques are used. Such studies should have treatments that simulate realistic management practices, over a wide range of site conditions. Additional emphasis should be placed on relevant soil and microbiological studies, and on chemical inputs from the atmosphere.

3. Nutrient losses by erosion are difficult to measure and evaluate. Generally, these losses are less than those of leaching losses in undisturbed forest ecosystems, but often exceed leaching losses in disturbed areas, at least for short durations. The major cause of accelerated erosion is road construction assocated with intensive harvesting. The impacts of the swift and sometimes catastrophic mass-flow types of erosion on removal of nutrients can be large but are usually impossible to measure accurately, let alone predict or control.

4. More studies are needed to clarify the impact of both leaching and erosional losses on actual productivity of forests. To date, studies have documented nutrient losses following intensive harvesting, but the anticipated drop in site quality following such losses is much more difficult to evaluate. Future studies should focus on this latter point, especially considering the impacts of the relatively new, whole-tree harvesting techniques.

5. Data on productivity decline related to erosion following harvesting are needed on an entire watershed basis. Chemical and physical changes in the soil, both at the site of erosion and at the site of deposition should be monitored. The decrease in surface erosion and the increase in mass movement, with time after harvest mean that long periods of evaluation are necessary. The best or most logical measurement period would likely be over a

rotation of the crop trees.

6. Researchers must maintain a realistic but somewhat skeptical attitude toward manipulation of natural ecosystems, and avoid "taking sides" where little baseline data exists.

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